

National Aeronautics and Space Administration

**Computing, Information and Communication Technologies Program
Information Technology Strategic Research Project
Intelligent Controls and Diagnostics Sub-Project**

Intelligent Flight Control Task UPN 302-05 FY04 Plan

Agreements:

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Approve: Level III ICD Sub-Project Manager

Date

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Submit: Level IV IFC Task Lead

Date

1. Background

Adaptive control technologies have been identified as one of the crucial needs of future NASA missions. The main focus of the Adaptive Control Technologies (ACT) group at NASA Ames (Code IC, NeuroEngineering) is to develop, implement, and test next generation control architectures that enable rapid prototyping of damage adaptive intelligent controllers. Intelligent control architectures rely on nature-inspired, mathematically sound problem solving tools and methodologies to arrive at a holistic approach that exploits, for a benefit, the order of reality as they exist. Critical application domains of relevance to NASA include

- Next Generation Launch Vehicle Technologies
- Orbital Space Plane
- Controls for life support
- Low thrust trajectory control & Aerobraking
- Free flyers & Unmanned Aerial Vehicles
- Formation flying applications
- Civil and military aircraft applications
- Aviation security
- Bio-Nano applications (proteomics, micro-fluidic circuits,

In this task, we examine two of the application domains of interest: low-thrust trajectory control and fault identification for aircraft and spacecraft using artificial immune systems.

2. Objectives

The objective of this research task is two fold:

(1) Develop Intelligent Flight Control technologies for JIMO-class spacecraft for providing the capabilities for on-board autonomous guidance, navigation, and control in the event of failures and uncertainties. Due to the lag in communication time and the limited thrust authority of low-thrust systems, a spacecraft operating in the outer-planets will need to have an on-board capability to determine its position, calculate where it should be along its trajectory based upon that positional information, and then command the spacecraft's thrust-level and direction.

(2) Develop an Artificial Immune System (AIS) based fault-verifying control algorithms for use in high performance aircraft and spacecraft. Specifically, we will examine these algorithms for reducing dead-bands in the response characteristics of direct adaptive control systems.

3. Technical Approach

To provide a real-time system capable of compensating for a broad spectrum of failures, ACT researchers have investigated a neural flight control

architecture for both flight and propulsion control. The concept was to develop a system capable of utilizing all remaining sources of control power after damage or failures. The Intelligent Flight Control (IFC) system uses an optimal allocation technique to ensure that conventional flight control surfaces will be utilized under normal operating conditions. Under damage or failure conditions, the system may allocate flight control surfaces, and incorporate propulsion control, when additional control power is necessary for achieving desired flight control performance.

In the past year, linear programming theory was used in conjunction with a cost function approach to provide generalized control reallocation over an arbitrary number of aircraft surfaces for the real-time control allocation problem. In the case of extreme damage to the plane, the original reference model may overdrive the remaining control surfaces and cause instability in the plane. Adaptive critic technology was utilized to modify the reference model in these cases. The goal is to develop a system that is capable of automatically compensating for a broader spectrum of damage or failures than the "daisy-chain" control allocation scheme currently used in INFPCS.

In this task, an extension to prior work is considered. This involves an innovation for fault detection: an Artificial Immune System (AIS) algorithm. Our prior milestones had established the benefits of intelligent flight control. One area of weakness that could be strengthened is the control "dead band" induced by commanding a failed surface. Since our approach uses fault accommodation with no detection, the dead band, although reduces overtime due to learning, is still present and causes degradation in handling qualities. This also makes it challenging for outer loop control design. If the failure can be identified, this dead band could be further minimized to ensure rapid fault accommodation and better handling qualities.

Artificial Immune System Architecture

Artificial Immune Systems (AIS) combine *a priori* knowledge with the adapting capabilities of biological immune systems to provide a powerful alternative to currently available techniques for pattern recognition, modeling, design, and control. Immunology is the science of built-in defense mechanisms that are present in all living beings to protect against external attacks. A biological immune system can be thought of as a robust, adaptive system that is capable of dealing with an enormous variety of disturbances and uncertainties. Biological immune systems use a finite number of discrete "building blocks" to achieve this adaptiveness. These building blocks can be thought of as pieces of a puzzle, which must be put together in a specific way to neutralize, remove, or destroy each unique disturbance the system encounters. There are several computational models that are based on the principles of immune systems. These are:

- Bone marrow models
- Negative-selection theorem

- Clonal Selection Algorithm
- Immune Network model
- Immunized Computational Systems

The assumption of usability of these models is preceded by the assumption that some understanding of the problem exists. This is akin to the vast source of information available to the immune system. Once this knowledge exists, one can use the immune sub systems individually or in combination.

Forrest et al developed a fault identification algorithm based on the principle of self-nonself discrimination in the immune system (Negative Selection Theorem). This discrimination is achieved in part by T-cells, which have receptors on their surface that can detect antigens. T-cells are generated by a random genetic rearrangement process and then they undergo a censoring in the *thymus* where the T-cells that react against self-proteins are destroyed. This algorithm is summarized as follows:

- Define self as a collection S of strings of length L over a finite alphabet--Needs to be protected.
- Generate a set R of detectors, each of which fails to match any string in S
- Monitor S for changes by continually matching the detectors in R against S . If any detector is matched, then a change is known to have occurred. Candidate detectors can be generated randomly or in an intelligent fashion.

Some of the applications of negative selection include: Color Image Segmentation; Anomaly detection in time-series data; and Computer virus detection. Our plan is to examine the AIS architecture as generic health maintenance architecture for aircraft and spacecraft applications. Under the FY'04 milestone, we will implement an AIS architecture for the C-17 aircraft as a fault-verifying system for improving the controller dead band after a failure.

Adaptive Control application to real-time low-thrust trajectory control

Future NASA missions will rely heavily on continuously controlled low-thrust spacecraft that can travel into deep space for exploring outer planets, their moons, and other space objects. Of the many challenges associated with such low-thrust missions, real-time on-board trajectory correction and adaptive inner-loop control has received the least attention. We plan to approach this problem as needing a hierarchical architecture based on the levels of intelligent control concept (A probable architecture is presented in the figure below). We will specifically focus on JIMO (Jupiter Icy Moons Orbiter) class of spacecraft as a test platform. Our milestones will include arriving at an architecture for real-time outer and inner-loop adaptive controller that will be fault accommodating.

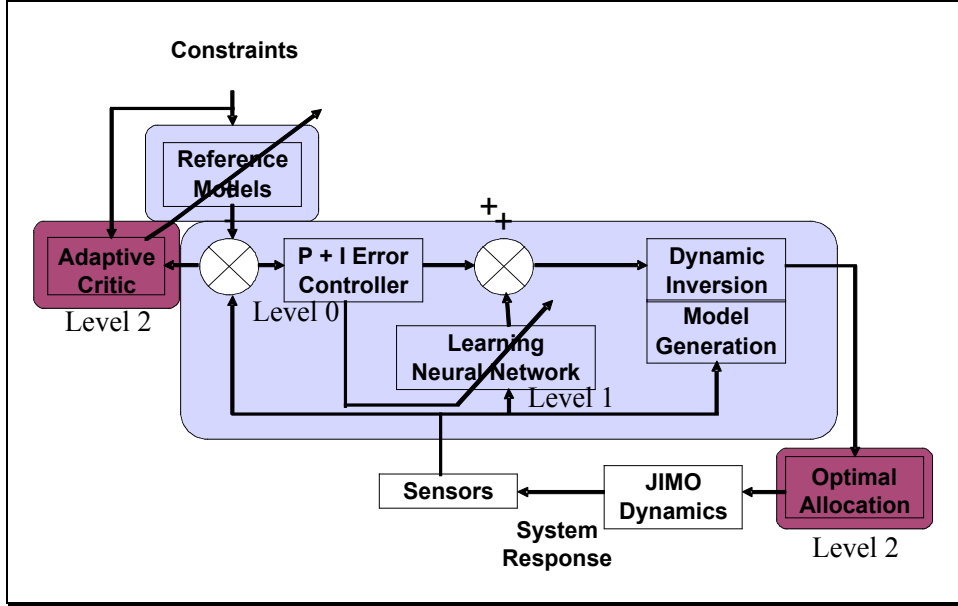


Figure: A hierarchical Level 2 Architecture for JIMO trajectory control

Adaptive Critics: Adaptive critic designs have been defined as designs that attempt to approximate dynamic programming based on the principle of optimality. Adaptive critic designs consist of two entities, an action network that produces optimal actions and an adaptive critic that estimates the performance of the action network. The adaptive critic is an optimal or near optimal estimator of the cost-to-go function that is trained (adapted) using recursive equations derived from dynamic programming. The critic is termed adaptive as it adapts itself to output the optimal cost-to-go function from a given system state. The action network is adapted simultaneously based on the information provided by the critic. The action network consists of any piece of the overall control architecture that has an effect on the final performance of the closed-loop system. In typical applications, the action network consists of the controller that is optimized using the critic. The inputs required for designing an adaptive critic design are

- The cost function or the performance measure.
- A parameterized representation of the critic.
- A parameterized representation of the action network.
- A method for adapting the parameters of the critic.

The choice of the cost function comes from the problem at hand. The cost could be distributed over the entire length of time or be defined at the end of the process. Typical examples of the two types are minimizing the fuel spent for a certain flight mission or intercepting a projectile where the utility depends only on the final error. Typically, the cost function can be given as,

$$(1) \quad J = \int_0^T U[x(i), u(i)]$$

where $U[x(i), u(i)]$ is the utility function or a penalty function that is a function of the state of the system, $x(i)$, and the control (action), $u(i)$, given to the system. ' γ ' is a discount factor that discounts the future performance.

The dynamic programming principle states that we can formulate an optimal control problem where we can get an optimal solution by minimizing the cost-to-go function, $J(t)$, which is defined as,

$$(2) \quad J(t) = \sum_{i=1}^{T-t} \gamma^i U[x(t+i), u(t+i)]$$

So the critic is designed to approximate the optimal form of this cost-to-go function or its derivatives with respect to the state of the system depending on the particular adaptive critic design.

4. Milestones

PCA 8 Project/Sub-Project Milestones	Due Date	Metrics
<i>8.4 Demonstrate a simplified adaptive flight control system that exhibits equivalent or improved levels of safety and handling qualities following damage.</i>	<i>Sep-05</i>	<i>Flight test results demonstrating a simplified adaptive flight control system provides equivalent or improved levels of safety and handling qualities following damage without the requirement for on-line parameter identification and/or other computationally expensive components. An adaptive flight control technique that is less complex, easier to implement, and can be retrofitted to existing flight control laws in modern aircraft.</i>
8.4.1 Preliminary design review of the simplified adaptive flight control system.	Jul-03	Analysis of the system performance, including simulation results under nominal and failure conditions. Final Technology Readiness Review (TRR) to be conducted at NASA Dryden Flight Research Center.
8.4.2 Hardware in the loop testing of the simplified adaptive flight control system.	Jan-04	Verified flight software, including all safety monitors, failure insertion routines, and data acquisition systems. Test results showing that the system is cleared for in-flight evaluation.
8.4.3 First flight demonstration of a simplified adaptive flight control system that exhibits equivalent or improved levels of safety and handling qualities following damage.	Sep-04	First flight demonstrating a simplified adaptive flight control system provides equivalent or improved levels of safety and handling qualities following damage without the requirement for on-line parameter identification and/or other computationally expensive components. An adaptive flight control technique that can be validated across a Class B Envelope (reversionary, clean up-and-away) under nominal and simulated failure conditions.

PCA 8 Project/Sub-Project Milestones	Due Date	Metrics
8.4.4 Post flight test analysis, reporting, and outreach.	Sep-05	Final report on flight test demonstrations, and print/multi-media development for educational outreach and external affairs. NASA Technical Memorandum or NASA Technical Paper documenting the approach, methodology, and analytical/experimental results that can be used as a substantive reference upon which future work can build upon. A conference paper and/or journal article in a relevant professional forum will also be developed and prepared and presented so that the results can be shared with the technical community at large.

Task Milestones and Schedule

Milestones	Description	Metrics
Trajectory implementation 2QFY04	Design and Implement trajectories of Jupiter and its moons of interest (Callisto, Ganymede and Europa).	Ability to generate trajectories for various time periods
Graphical Simulation Visualization tool 3QFY04	Provide a Graphical capability for simulating flyovers of Jupiter's moon Callisto, Ganymede and Europa.	Ability to generate varying scales of visualization of the trajectories in the reality center at NEL
ALTA Version 0.5 3QFY04	Controlled trajectory using a point mass model and the ALTA architecture.	Test results showing the benefit of ALTA technologies using a point mass model as the spacecraft.
Adaptive Low-Thrust Architecture (ALTA) prototype ALTA Version 1.0 4QFY04	Implementation and testing of real-time trajectory correction/adaptive control using JIMO-class spacecraft rigid body model	Test results showing the benefit of ALTA technologies using a realistic simulation environment.
Multi-level Immune Learning Detection (MILD) system prototype 3QFY04	Design implementation and testing in the Neuro Engineering Simulation Facility of the fault verifying IFC using an artificial immune system.	An improvement in the handling qualities using fv-IFC.

5. Resources / Budget

Labor:

2.00	FTE
2.00	WYE

Procurement (excluding labor):

\$0.148M	Procurement
\$0.038M	SERV-I

6. Management Approach

Deliverables (FY 2004):

- Research Technical Paper compliant with Ames Publication procedures (ARC 310 and ARC 1676), or equivalent procedural compliance for tasks located at NASA Glenn Research Center.
- Simulation / demonstration of technologies.
- Physical / experimental data acquisition and/or technology validation.

Environment / Equipment:

- All research will take place in the NeuroEngineering Laboratory Rm. 281 / Bldg. 269, Flight simulation facilities (CVSRF in Bldg. 257 or the VMS in Bldg. 243), and Flight test assets (AFDD OH-58C and DFRC F-15 Tail No. 837).

Compliance with Standards and Codes:

- 53.ARC.0009.2.1 Publication of research
- 53.ARC.0009.2 Management and performance of research

Applicable Quality System Procedures and Work Instructions:

- 53.ARC.0004.1
- 53.ARC.004.2

Process Monitoring Methods/Procedures:

- Performed to satisfy all Level I business requirements, described below:

Type	Frequency	Purpose	Reporting By	Content/Format	Comments
Technical Highlights	Weekly	Status updates and/or highlights	L4 Task Leads and Technical POCs	Informal text of monthly progress - indicate "None" for negative replies <i>e-mail text; web-site entry</i>	Unless significant progress is reported, can be brief
Quarterly Progress	Quarterly	Program Management Council (PMC)	L2 Managers	Text (and accompanying graphic, if any) of quarterly progress towards L1/L2 milestones <i>e-mail text; electronic copy of graphic; web site entry (under development)</i>	Progress towards all active L2/L3 milestones should be reported
Technical Highlights	Quarterly	Program advocacy and reviews	L2 Managers	One page text (Bullets: Objective, Background, Accomplishment, Future Plans) and one page graphic <i>e-mail text; electronic copy of graphic; web site entry (under development)</i>	Technical Highlights are used to promote the CICT Program and represent significant accomplishments
Milestone Summaries	Milestone due dates or	Program advocacy and	L2 Managers	Detail description of milestone accomplishments relative to goals	

	completion	reviews		and success metrics. Background material including graphics, technical reports, publications, etc. <i>e-mail text, electronic copies of graphics, hardcopies of reports</i>	
Budget and Workforce Tracking	Monthly (5th working day of each month)	Status reports to ITSRO and CFO	Center POCs for resource management	Spreadsheets, graphs at the 5-digit level. Include variance explanation for +/- 10% variances <i>e-mail text; electronic copy of graphs; web site entry (under development)</i>	Planned vs. actual commitments obligations and accruals at 5-digit level. Planned vs. actual CS and SSC workforce.
ATAC Sub-committee Reviews	Annual	To review and provide advice on research efforts	L1, L2, and L3 Managers and Technical POC's	Program, project, and sub-project plan on-site review on status, approach, and technical accomplishments	
LCPMC	Annual	To review status, budget, and milestones	L1 and L2 Managers	Program and Project tracking of budget and milestones	